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TECHNICAL REPORT NO. 65-119

QUARTERLY REPORT NO. 1, PROJECT VT/5051, DEEP-WELL RESEARCH

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TECHNICAL REPORT NO. 65-119

QUARTERLY REPORT NO. 1  
PROJECT VT/5051, DEEP-WELL RESEARCH

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## CONTENTS

	<u>Page</u>
ABSTRACT	
1. INTRODUCTION	1
2. ASSEMBLE AND OPERATE VERTICAL ARRAY SYSTEMS, TASK 1a	1
2.1 Vertical array of vertical seismometers	1
2.2 Vertical array of triaxial seismometer	2
3. MAINTAIN AND OPERATE TEST SITE; EVALUATE DEEP-HOLE DEVICES, TASK 1b	3
4. MAKE FIELD MEASUREMENTS, TASK 1c	3
5. DATA ANALYSIS, TASK 1d(1)	6
5.1 Theory of Rayleigh waves	6
5.2 Water-generated noise at Grapevine, Texas	8
5.3 P-wave amplitude-depth relationships	10
6. ARRAY PROCESSOR, TASK 1d(2)	13
APPENDIX 1 - Statement of Work to be Done	
Ammended Statement of Work	

## ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Frequency response of deep-hole seismograph at GV-TX using Model 11167 seismometer and Model 4300 PTA with 10 cps galvanometer and 10 cps low-pass filter (Model 6824-11). Seismometer damped 17 to 1. Galvanometer damped 0.7 critical. Seismometer at depth of 2700 m.	4
2	Recording of event by surface seismograph and deep-hole seismograph at Grapevine, Texas. Deep-hole seismograph has high frequency response altered through use of 10 cps galvanometer. Epicenter unknown. Magnifications at 1 cps (X10 enlargement of 16-mm film) Deep-hole seismometer at 2900 m.	5
3	Recording of ECOOE 1 ton shot by surface seismograph and deep-hole vertical array at Franklin, West Virginia. Epicenter $34^{\circ}23.3'N$ , $77^{\circ}02.1'W$ . Magnification at 1 cps (X10 enlargement of 16-mm film). DHA-1 at 3660 m, DHA-2 at 1830 m, DHA-3 at 15 m.	7
4	Amplitude-depth relationships at FO-TX obtained by changing the P-wave velocity, S-wave velocity and densities below the hole from the original mode.	9
5	Probability of occurrence and percentage of occurrence of the 0.1 - 1.4 sec noise in the deep hole at 2280, 2580, and 2880 m. GV-TX	11
6	Power ratio (deep-hole spectrum divided by surface spectrum) of a teleseismic signal recorded at 2881 m, Apache, Oklahoma	12
7a	Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.	14
7b	Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.	15
7c	Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.	16

### ILLUSTRATIONS, Continued

<u>Figure</u>		<u>Page</u>
7d	Results of inverse filtering of a small teleseism at Apache Oklahoma. Filtered and unfiltered traces are shown.	17
8a	Teleseism recorded at Apache, Oklahoma, by the shallow-hole (18 m) seismograph.	18
8b	Seismogram obtained at 1970 m after inverse filtering, Apache, Oklahoma.	19
8c	Seismogram obtained at 2270 m after inverse filtering, Apache Oklahoma.	20

## ABSTRACT

Vertical arrays of four vertical seismometers were operated in the deep hole at sites near Apache, Oklahoma, and Franklin, West Virginia. At each site a fifth deep-hole seismometer was operated in a shallow hole adjacent to the deep hole as a surface reference. The deep hole near Apache was filled with water to within 75 m of the surface. Measurements at this site were interrupted when the hole was filled and have not resumed. Design improvements to the deep-hole, short-period triaxial seismometer were completed. A vertical array of up to four triaxial seismometers in one hole was designed and is under construction.

The normal response of the deep-hole vertical seismograph was modified to peak at higher frequencies by use of a 10-cps galvanometer and auxiliary-filter amplifiers. Also, work was done to extend the response of both the vertical and the triaxial seismographs to provide long-period responses peaked near 20 seconds.

The test site near Grapevine, Texas was maintained in operation to perform tests and experiments on the triaxial seismometer. Additionally, seismographs with special responses were tested there.

Results of data analyses indicate that changes in the shear velocities assumed in the Rayleigh wave computer program do not appreciably change the amplitude-depth relationships. Spectral analyses of teleseismic P waves indicate that enough S-wave energy is present to degrade the filters that eliminate the surface reflections. Several examples of the results of attempts to eliminate the surface reflections are shown; results are good for the first few cycles.



QUARTERLY REPORT NO. 1, PROJECT VT/5051  
DEEP-WELL RESEARCH

1. INTRODUCTION

This report discusses a project of research in deep-hole seismology. The work reported herein covers assembly of deep-hole array systems, field measurements, analysis of data, and design of a digital data acquisition system.

The purpose of the report is to present the technical findings and accomplishments of this project from 1 August 1965 through 30 September 1965 and is submitted in compliance with paragraph 2, Reports, of the Amended Statement of Work to be Done, AFTAC Project Authorization No. VELA T/5051 dated 19 May 1965. The project is under the technical direction of the Air Force Technical Applications Center (AFTAC) and under the overall direction of the Advanced Research Projects Agency (ARPA).

The main body of the report is presented in the same sequence as the tasks in the Statement of Work. Copies of the Statement of Work and of the Amended Statement of Work are included as appendix 1.

2. ASSEMBLE AND OPERATE VERTICAL  
ARRAY SYSTEMS, TASK 1a

2.1 VERTICAL ARRAY OF VERTICAL SEISMOMETERS

At the time of the last Semiannual Report, dated 24 August, a vertical array of six Model 11167 Seismometers had been operated at the GV-TX site near Grapevine, Texas; and a three-element array plus two additional seismometers were then operating at the AP-OK site near Apache, Oklahoma. During the period of this report the array continued in routine operation at AP-OK until the end of September. At that time operation was suspended by agreement between the Project Officers of VT/5051 and VT/4051 so the van could be moved for use in the Long Range Seismic Measurements (LRSM) program.

The FN-WV site, near Franklin, West Virginia operated with two seismometers in the deep hole and a third in the shallow hole until late in August, when a vertical array of three seismometers was installed. As in the AP-OK installation, a fourth instrument was installed above the array in the deep hole, and a fifth seismograph was operated in a shallow hole nearby.

## 2.2 VERTICAL ARRAY OF TRIAXIAL SEISMOMETER

In the last Semiannual Report of this project, the evaluation of the Triaxial Seismometer, Model 22700 was discussed. The modifications mentioned in that report have been completed and two prototype units are under construction.

Each of the triaxial seismometers consists of three identical seismometer modules plus one switch module and one hole lock. Each seismometer module is a complete seismometer with a spring-mass system, calibration coil, weight-lift calibrator, mass centering and locking motor, and other controls and switches. The sensitive axes of the three modules are orthogonal and inclined 35.3 degrees from horizontal. The switch module located above the three seismometer modules permits the three seismometer modules and the hole lock to operate on a single, seven-conductor cable. The switch module permits separate calibration of each seismometer module and operation of all three modules with fully independent and separated data lines.

Our original plan was to operate two triaxial seismometers (six modules) on a single cable using a common ground lead for the data coils. This is not considered practical now due to the large amount of noise from power lines (which also are grounded) and other electrical noise sources. A method of handling the triaxial seismometers has been designed that will enable two seismometers to be installed by a single winch unit using two cables. Thus, each field team can install four triaxial seismometers in a single hole using two winch trucks. This concept will be tried first at the GV-TX site in October following a thorough laboratory evaluation of the triaxial seismometers now under construction.

### 3. MAINTAIN AND OPERATE TEST SITE; EVALUATE DEEP-HOLE DEVICES, TASK 1b

The site near Grapevine, Texas, continues to be maintained primarily as a test facility to develop and evaluate deep-hole devices. In this connection, one module of the triaxial seismometer was evaluated as a long-period device. Efforts were made to shift the response to center near 20 seconds and amplify the resulting very weak signal to a usable value. These efforts indicated that the inherent noise levels of the best amplifiers available were about the same magnitude as the seismic signals at that low frequency. These results led to a further examination of the theoretical low-frequency limits of the Model 11167 seismometer. At this time the Bureau of Standards is computing for us the theoretical limits of both the triaxial and the deep-hole vertical instruments with various combinations of amplifiers.

Work was also done at GV-TX on evaluating the use of the seismograph with its response shifted to center near 8 cps. This is a much easier problem since the seismometer's output amplitude does not decrease above its natural frequency as it does on the long-period side. Figure 1 shows a record made at GV-TX using the Model 11167 and a 10-cps galvanometer in the phototube amplifier. Figure 2 shows a response obtained through use of a high-pass filter. Additional shaping could be obtained by shifting the natural frequency of the seismometer to a higher value or through use of additional filters.

Recently a temperature survey of the deep hole at GV-TX was run. The results show an anomaly at a depth near 2,500 m. This is discussed further in section 5.2 of this report.

### 4. MAKE FIELD MEASUREMENTS, TASK 1c

During the period of this report routine field measurements were made at AP-OK and at FN-WV.

At AP-OK routine operation of a vertical array of three seismometers on one cable, plus a fourth seismometer on a second cable continued in the deep hole until near the end of September. A fifth deep-hole seismometer was operated in a nearby shallow hole. The fourth seismometer on its own cable was operated in the upper sections of the deep hole. This permits the upper instrument to be moved up and down easily to obtain signals from various points in the hole.

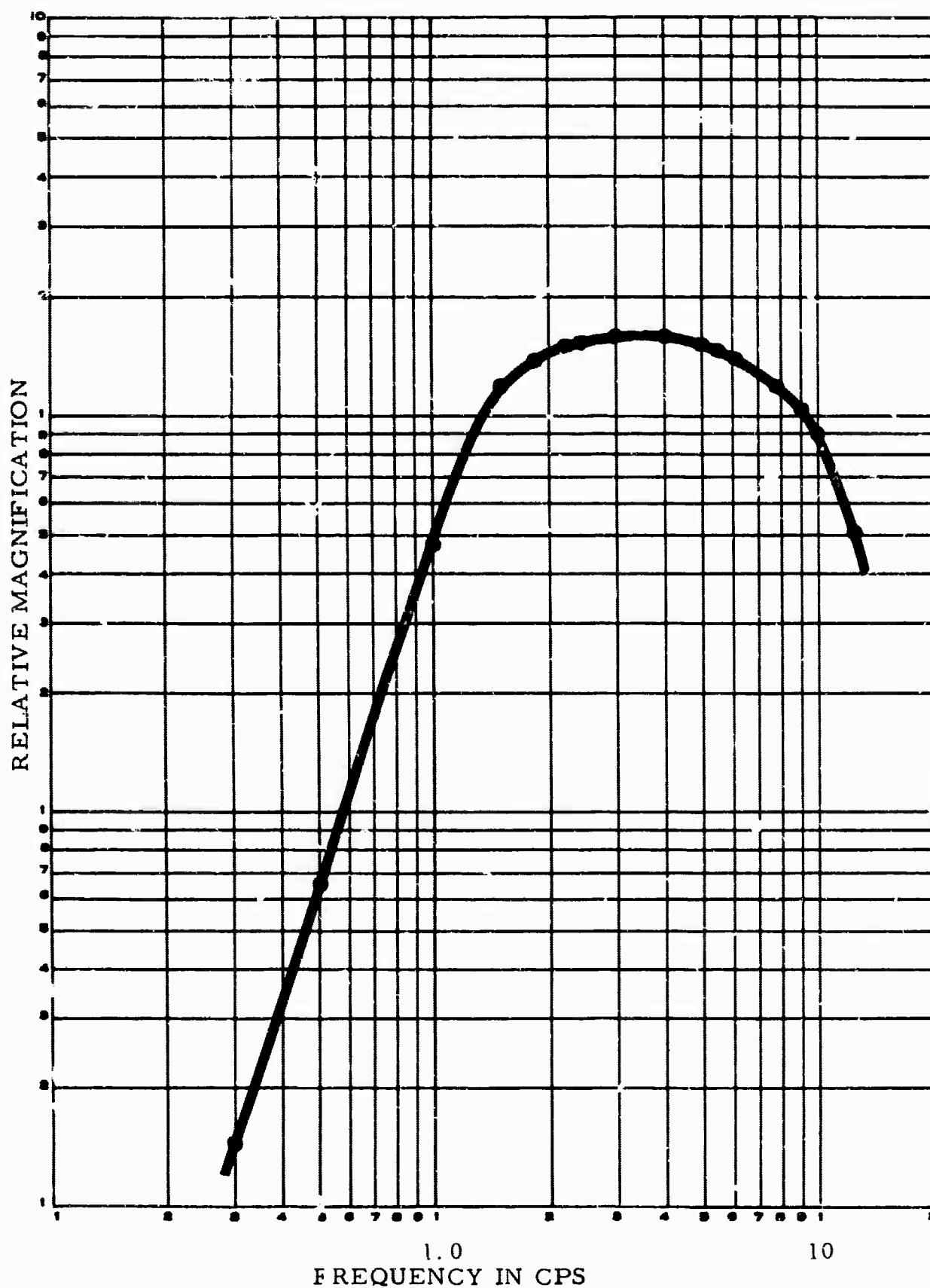


Figure 1. Frequency response of deep-hole seismograph at GV-TX using Model 11167 seismometer and Model 4300 PTA with 10 cps galvanometer and 10 cps low-pass filter (Model 6824-11). Seismometer damped 17 to 1. Galvanometer damped 0.7 critical. Seismometer at depth of 2700 m.

10 September 1965

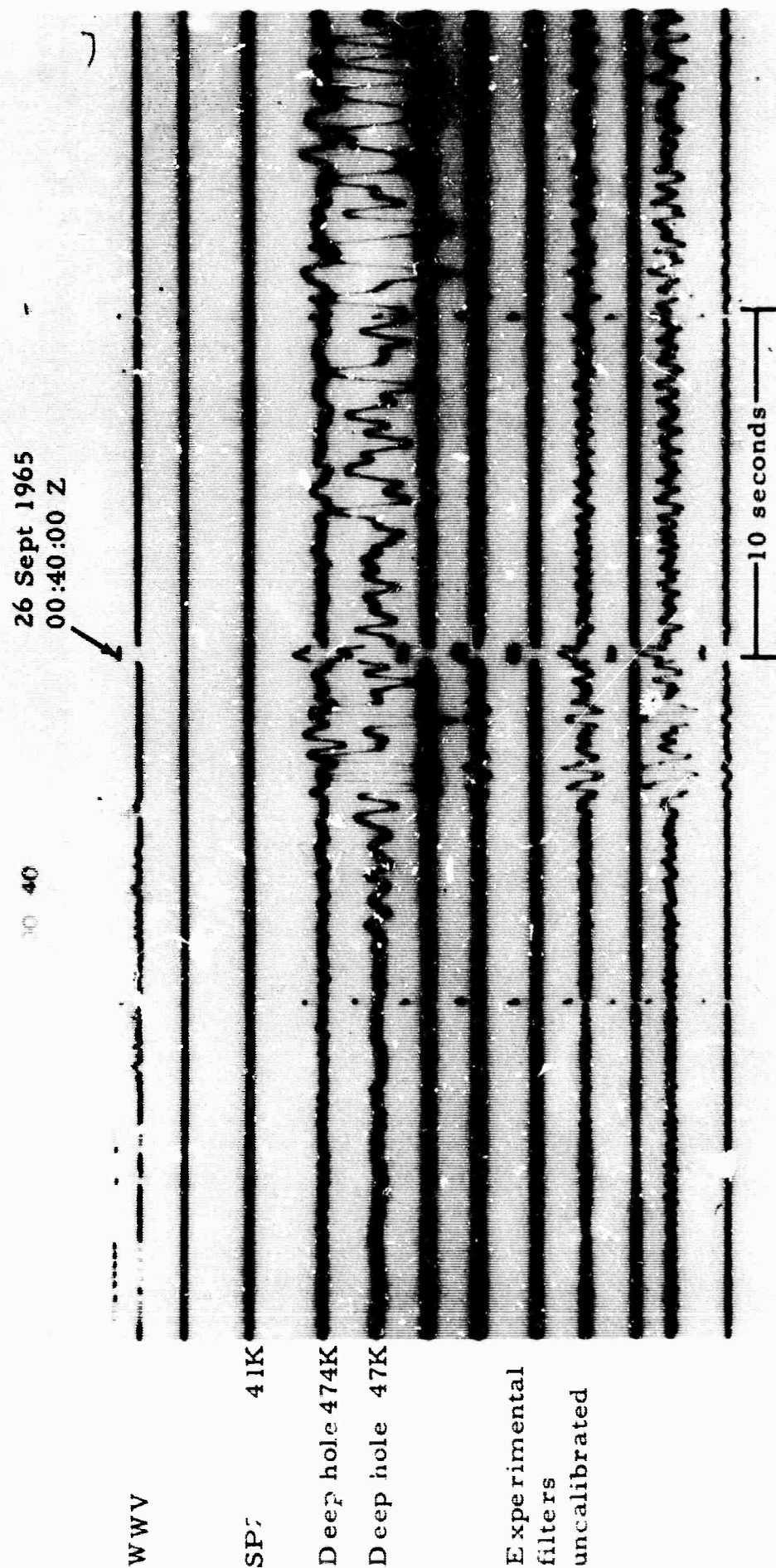


Figure 2. Recording of event by surface seismograph and deep-hole seismograph at Grapevine, Texas. Deep-hole seismograph has high frequency response altered through use of 10 cps galvanometer. Epicenter unknown. Magnification at 1 cps. (X10 enlargement of 16 mm film) Deep-hole seismometer at 2900 m. 236

When the array was installed, an unusual amount of 1-cps noise was noticed in the instrument near the bottom and this was thought to be caused by the presence of about 0.3 km of water in the hole. Consequently, on 12 September, the hole was filled with water to within about 75 m of the top. When the hole was filled, defective pressure seals allowed three seismometers to become flooded. Since repairs were not complete at the time the van was moved, for Long Shot, the instruments and equipment were brought into the Garland laboratory for a complete overhaul. It was found that the seals that failed were of types that had failed in other installations and had been redesigned. These instruments had been in the dry hole at GV-TX and replacement of the seals was overlooked when the move to AP-OK was made.

The AP-OK site was closed near the end of September to permit the team and van to participate in Project Long Shot at another site.

At the FN-WV site two seismometers were operated in the deep hole from May 1965 until August 1965. Figure 3 shows a recording of one of the shots exploded offshore as a part of ECOOE project in June and July. The three seismometer arrays have operated routinely since August, and will continue in operation during Long Shot. Three of the five deep-hole seismometers will be equipped with high frequency galvanometers early in October. The response will be similar to that shown in figure 1.

## 5. DATA ANALYSIS, TASK 1d(1)

### 5.1 THEORY OF RAYLEIGH WAVES

Experimental results from noise measurements indicate that the agreement between theoretical and experimental Rayleigh wave amplitude-depth relationships is often not as good as expected (see, for example, Semiannual Report No. 2, VT/5051). A number of suggestions have been made to account for these discrepancies.

The experimental results could be explained by the presence of an appreciable percentage of body waves in the noise; however, despite considerable effort, body waves have only been shown to exist at frequencies greater than 2 cps and not at the lower frequencies of greatest interest.

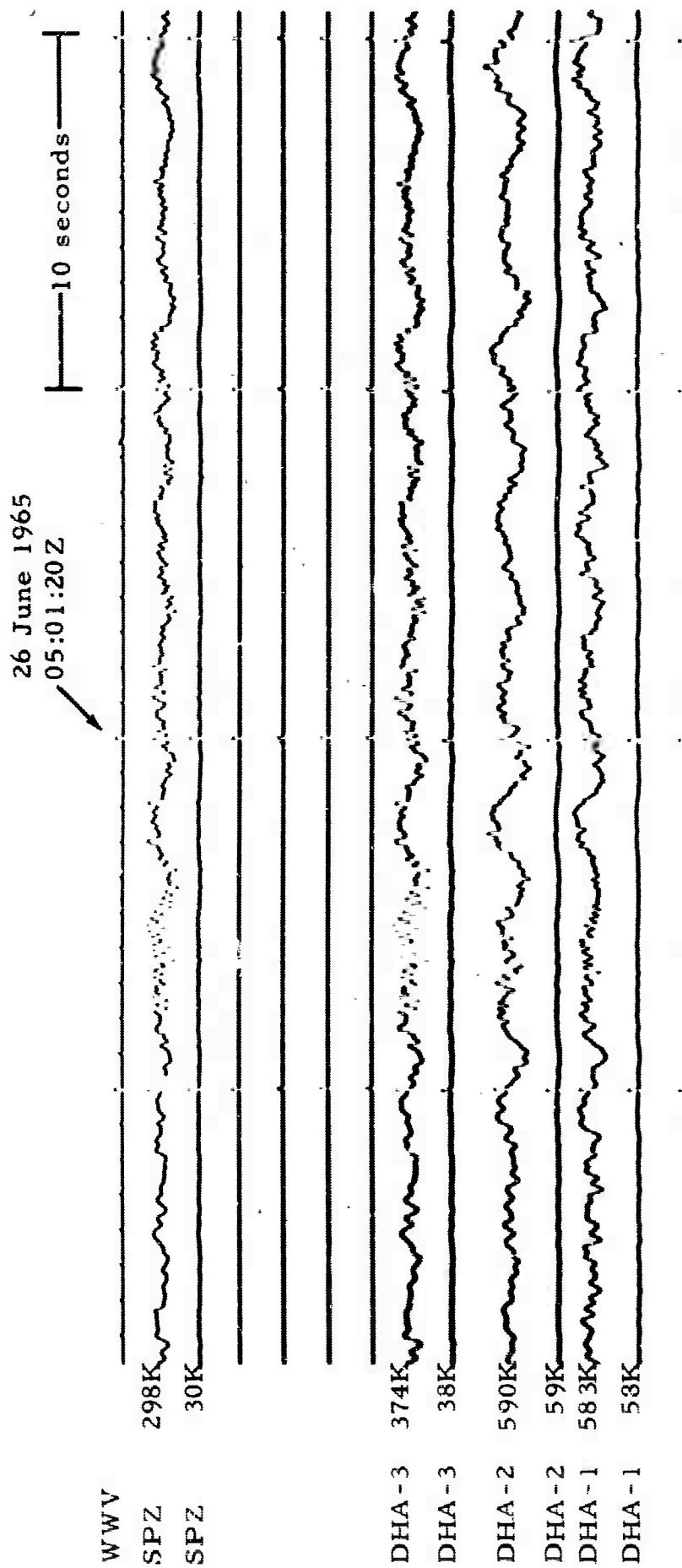


Figure 3. Recording of ECOOE 1 ton shot by surface seismograph and deep-hole vertical array at Franklin, West Virginia. Epicenter 34°23.3'N, 77°02.1'W, magnification at 1 cps (X10 enlargement of 16 mm film). DHA-1 at 3660 m, DHA-2 at 1830 m, DHA-3 at 15 m

In sedimentary sections the well known velocity anisotropy of shales, which is not taken into account by the Rayleigh-wave computer program presently used, could possibly be used to explain the discrepancies. However, this anisotropy will not explain the difficulty at sites where no appreciable thickness of shales is present.

It is also possible that the S-wave velocities and densities used in the theory are not correct. Of the information necessary to obtain the theoretical behavior of Rayleigh waves (P and S velocities, and densities), only the P-wave velocities in the hole are known with accuracy. The velocities and densities below the hole and the S-wave velocities and densities in the hole are assumed from the best information available on the parameters of the rocks present.

Figure 4 shows a few examples of the results obtained when the velocities and densities are changed. Only minor changes are observed in the amplitude-depth relationships in the hole. A large number of computer runs have been made while changing the unknown parameters slightly. Although the results have not been completely evaluated, it appears that changing S-wave velocities and densities (within reason) in the hole is not likely to change the amplitude-depth relationships sufficiently to explain the discrepancies. A complete evaluation of these results will be reported later.

Another interesting possibility is being investigated at present. Drs. Gene Simmons and Mark Landisman (personal communications) have suggested that a low-velocity layer exists in the crust at depths of approximately 10 km. A low-velocity layer would result in large displacements in the layer for those Rayleigh modes that reach to this depth. If a Rayleigh mode travels with most of its energy content in a homogeneous low-velocity layer, the wave would travel with less attenuation than a wave with its energy concentrated in the inhomogeneous surface layers. If this layer exists it could possibly explain the presence of certain modes at given periods, for example, the first higher mode at about 3.0-sec period.

## 5.2 WATER-GENERATED NOISE AT GRAPEVINE, TEXAS

Temperature measurements made in the GV-TX hole by Dr. Simmons of Southern Methodist University (under sponsorship of AFOSR Grant 418-65) indicate that water may be flowing behind the casing. The reason for this conclusion is an abrupt temperature change at a depth of 2,420 m. It is possible that there is a water flow from an aquifer at this depth to an over



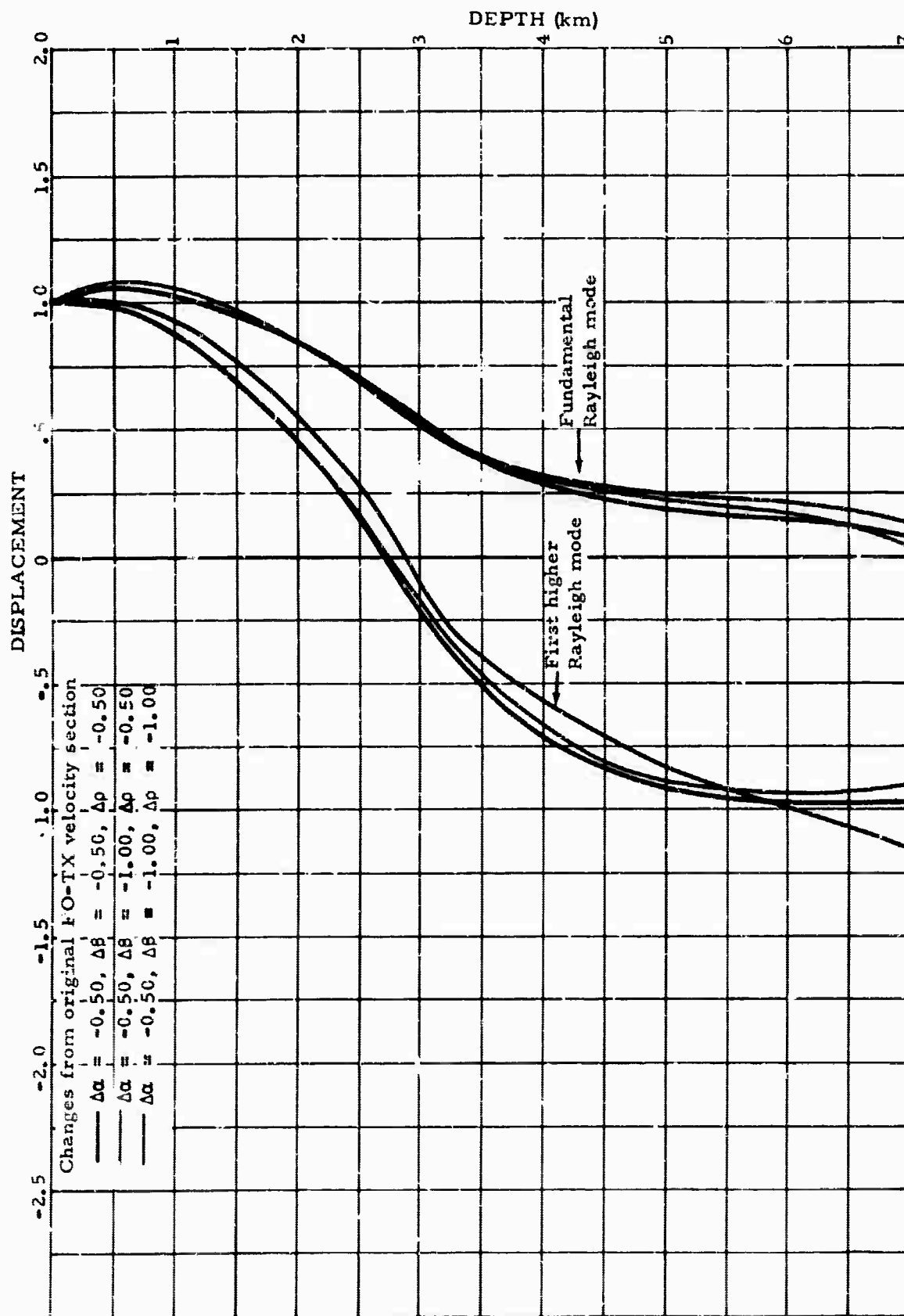


Figure 4. Amplitude-depth relationships at FO-TX obtained by changing the P-wave velocity, S-wave velocity, and densities below the hole from the original model

depth whose location has not been determined; however, it does not appear to be the bottom of the hole. The casing is cemented from the bottom upward to a depth of 2,650 m. The water flow is therefore probably confined to the depth interval of 2,420 m to 2,650 m.

Examination of noise surveys conducted in the past did not show an increase in noise level at depths between 2,650 m and 2,420 m. However, a noise survey conducted after the water flow was observed indicated an increase of the noise level at 2,580 m, as compared to noise levels on either side of this depth (see figure 5).

### 5.3 P-WAVE AMPLITUDE-DEPTH RELATIONSHIPS

Inverse filters that eliminate surface reflections recorded by deep-hole seismographs are critically dependent on the exact behavior of P waves with depth. In general, comparisons between the experimental and theoretical measurements of P waves at depth have not shown as good agreement as expected. We have begun to study this problem in detail. Before investigating more complex velocity sections, signals from the Apache, Oklahoma, array were used because of the simple velocity section present at this site. The experimental data were obtained from spectral analyses of large earthquakes (high signal-to-noise ratio). The first 30 sec of the signals were used. The theory necessary to study the results has previously been reported (Semiannual Report No. 2, VT/5051). It is only necessary to omit the integral sign in the formulas given for incident P waves.

Figure 6 shows a typical example of the results obtained. The agreement between theory and experiment is quite good except for the second order minima at 0.80 sec and 1.15 sec. These minima could not be obtained by changing any of the parameters, such as Poisson's Ratio, in the theoretical program. The most likely possibility is that they are the result of interferences from transmitted S waves derived from a P wave incident upon the crust-mantle interface. However, models which take this particular interference phenomena into account cannot be adequately treated without information regarding the nature and thickness of the crust beneath the Apache site. Attempts will be made to obtain the arrival times and amplitudes of S waves in the signal in order to obtain the information necessary to construct the inverse filters so that they will not only eliminate the surface reflection but also S waves present in the signal. This is a difficult problem and it is not expected that positive results will be obtained in the near future.

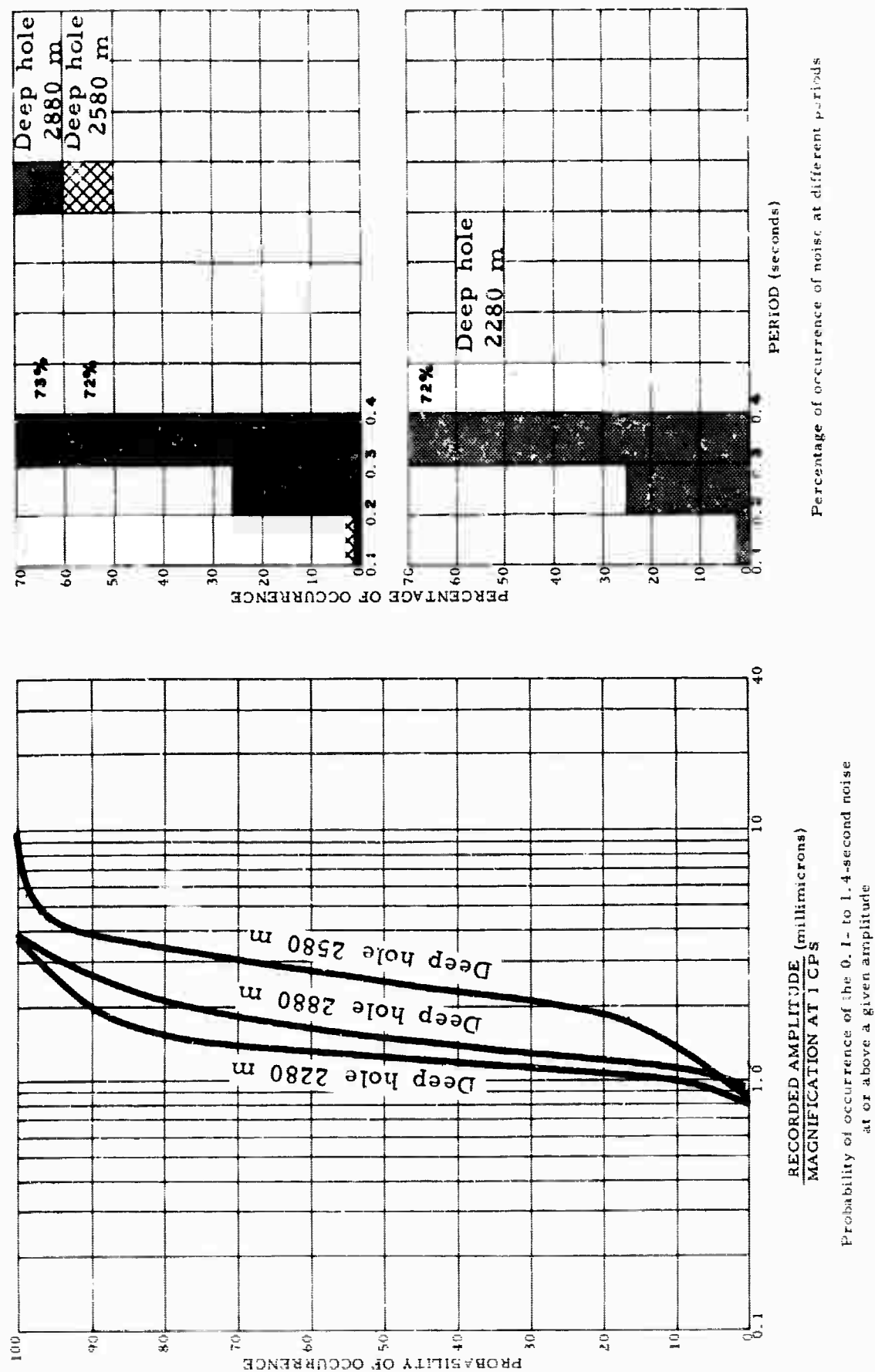


Figure 5. Probability of occurrence and percentage of the 0.1-1.4 sec noise in the deep hole at 2280, 2580, and 2880 m. GV-TX

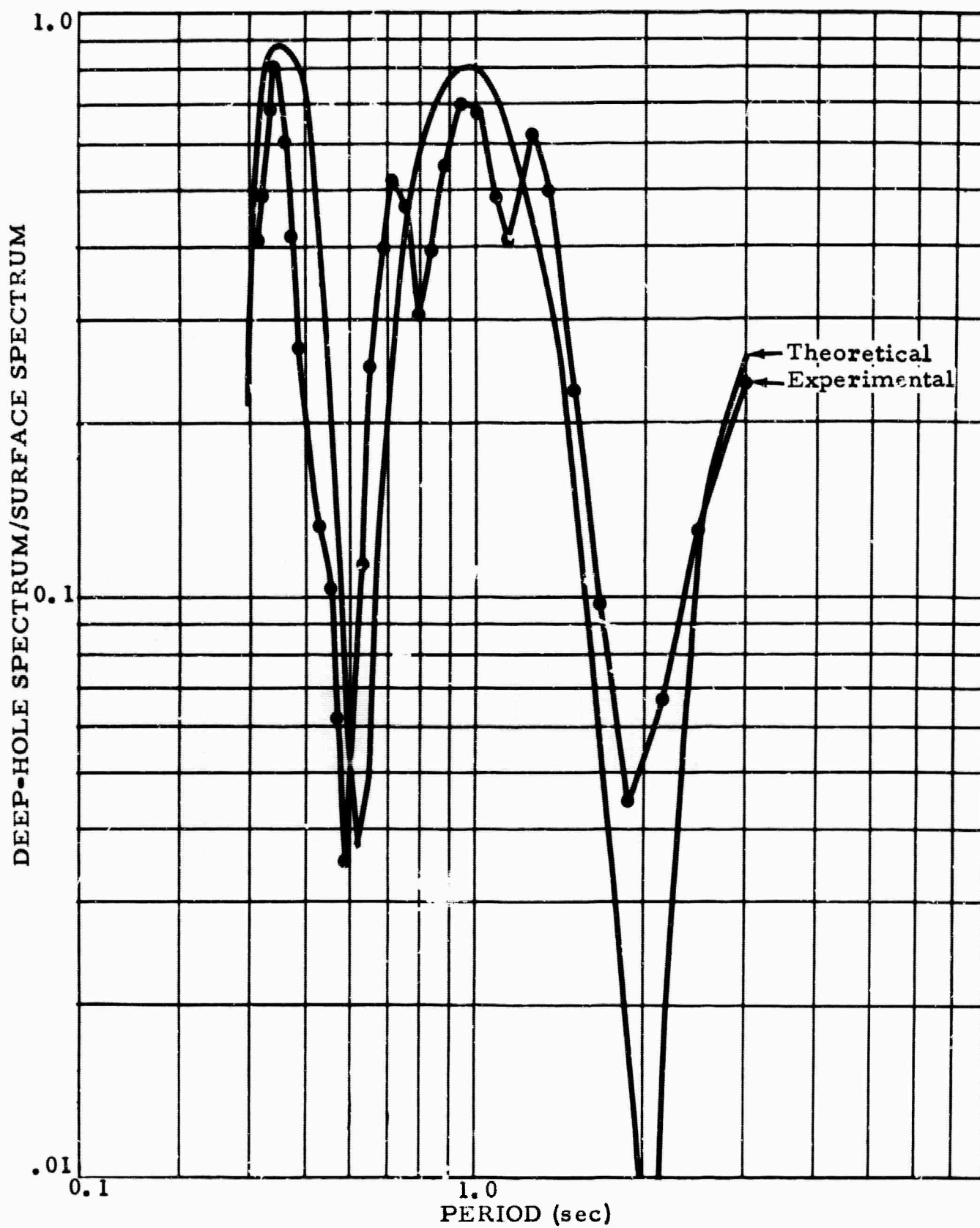


Figure 6. Power ratio (deep-hole spectrum divided by surface spectrum) of a teleseismic signal recorded at 2881 m. Apache, Oklahoma

## ARRAY PROCESSOR TASK 1d(2)

Work is continuing in developing the inverse filters described previously in Semiannual Report No. 2, Project VT/5051. Figure 7 shows the results obtained with a small signal from the Apache array. The filters worked well for the depths of 2881, 1970, and 1660 m. The differences between the surfaces and the deep-hole traces are on the order of the background noise that is contaminating the signal. The same figure also shows one of the problems that is being encountered. The filtered trace from a depth of 1360 m continues to ring after the signal amplitudes should have become very small. The exact reason for this behavior has not been determined; however, an error in the up-hole time used for the filter is the most probable cause. These filters are quite sensitive to small errors in measured un-hole time. Figure 8 shows an example of inverse filtering of the deep-hole traces on a large signal from a distance of 70 deg. Examination of the deep-hole traces with the surface (18 m) trace indicates that the first three cycles are nearly identical. This was true for all four deep-hole traces although only two are shown in the figure. After the first three cycles the agreement is not as good. Examination of horizontal-motion seismograms shows appreciable S-wave energy after the first few cycles of the signal. The present filters cannot eliminate the S waves generated in the crust below the hole. The filters as they are used at present tend to introduce some high-frequency noise into the seismograms. It is hoped that this problem can be eliminated by limiting the pass band (for example from 0 to 5 cps) of the filter. The delta function filters used at present essentially assume that all frequencies are present. The filters need to cancel the surface reflection very well if further processing of the array is to be effective. Therefore, other approaches to the inverse filtering problem are going to be considered. A computer program is being written to try to eliminate the surface reflection by a signal-channel Wiener filter. The input to the program will be the autocorrelations and cross correlations of the signal. These can be obtained from theoretical considerations or experimental results. Both approaches will be tried in the next several weeks to determine which of the different types of filters eliminates the surface reflection most effectively.

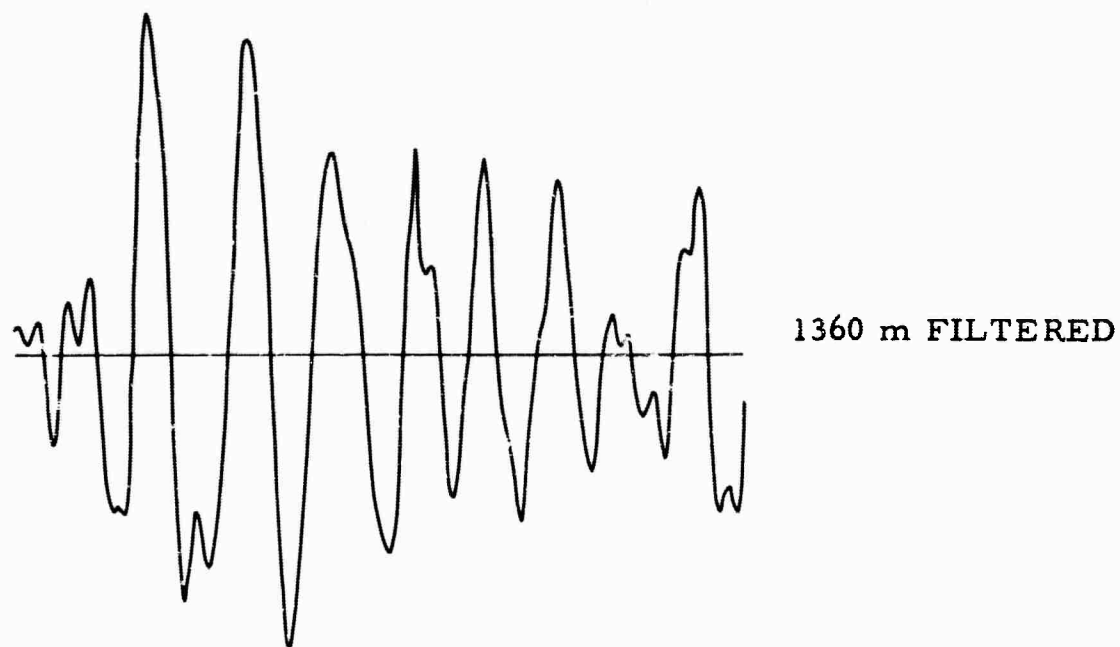
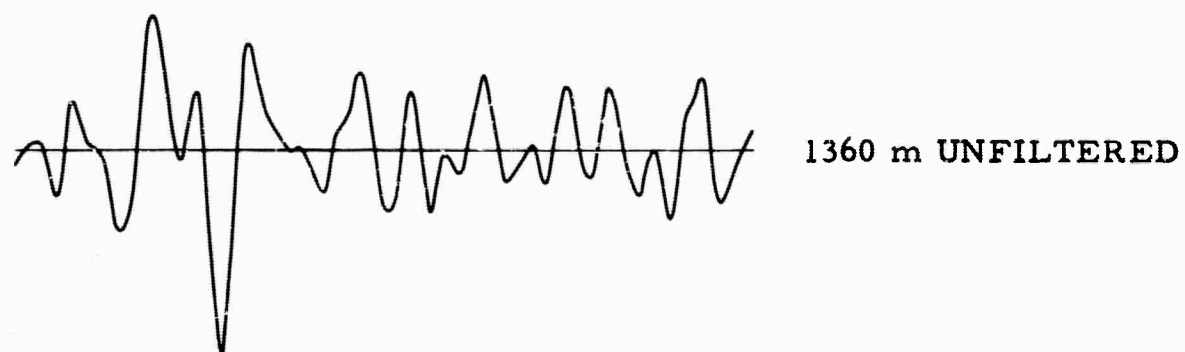
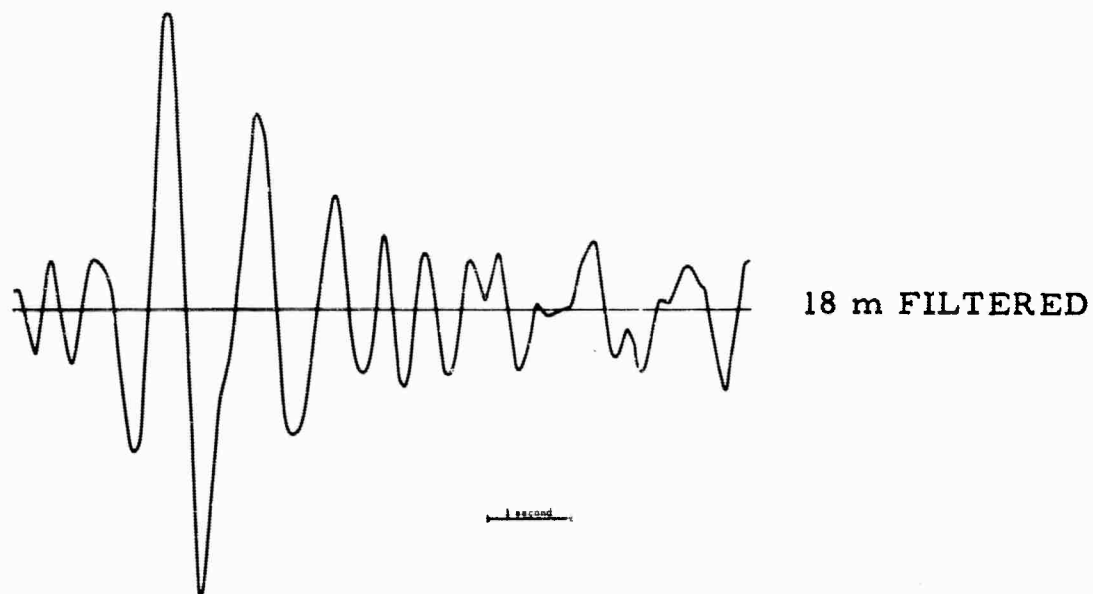


Figure 7a. Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.

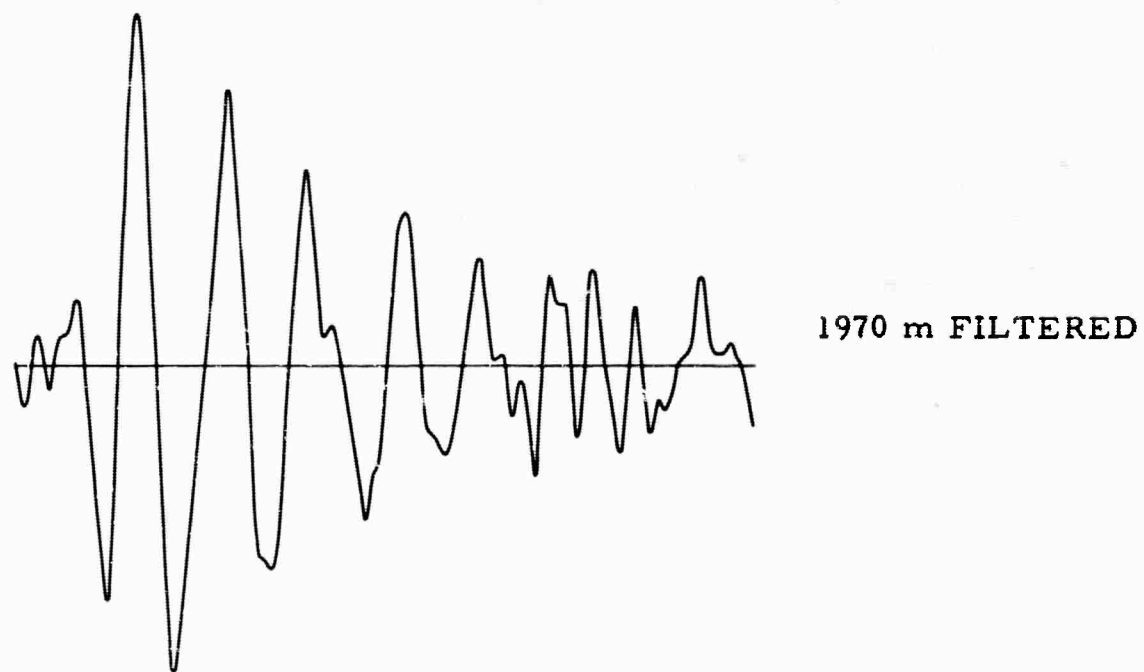
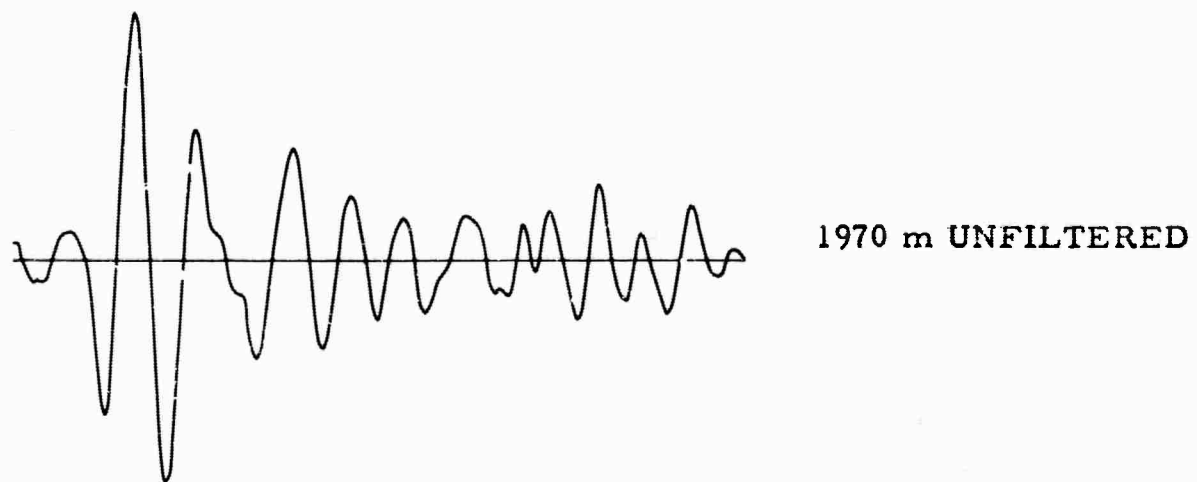
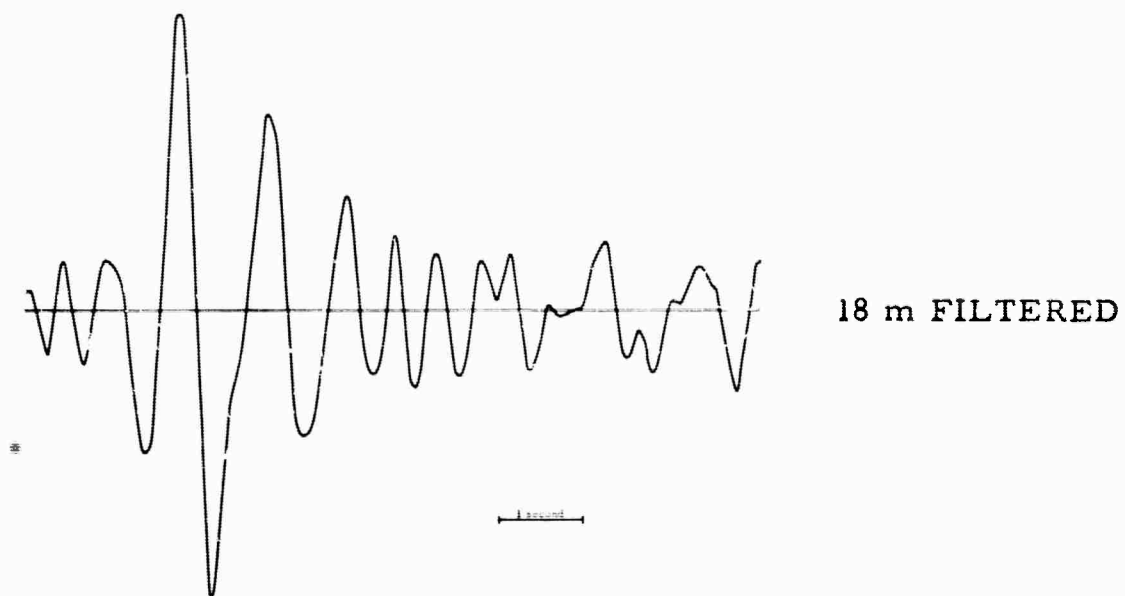
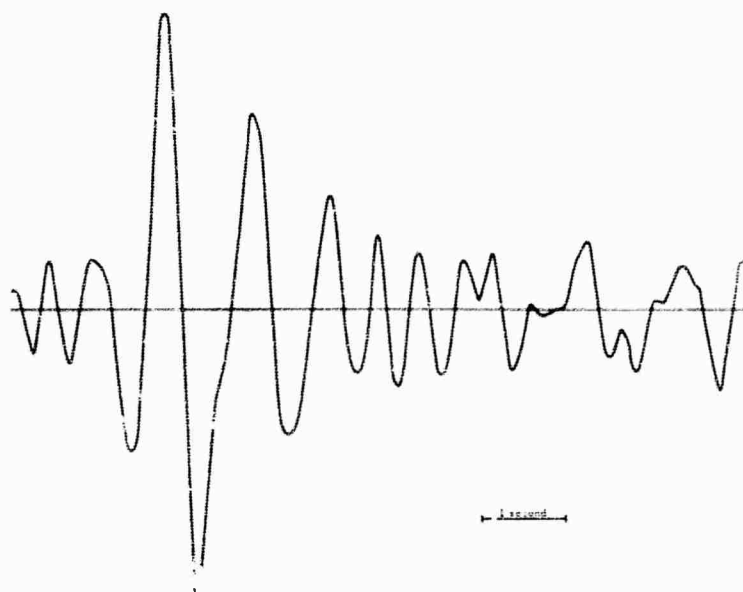
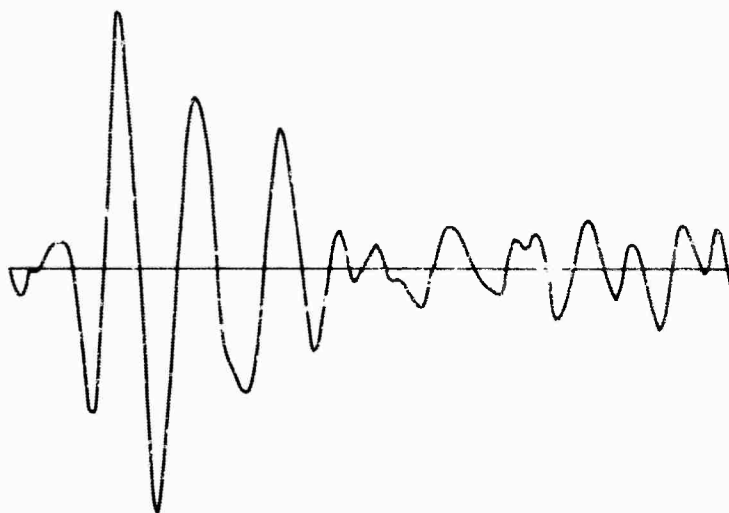


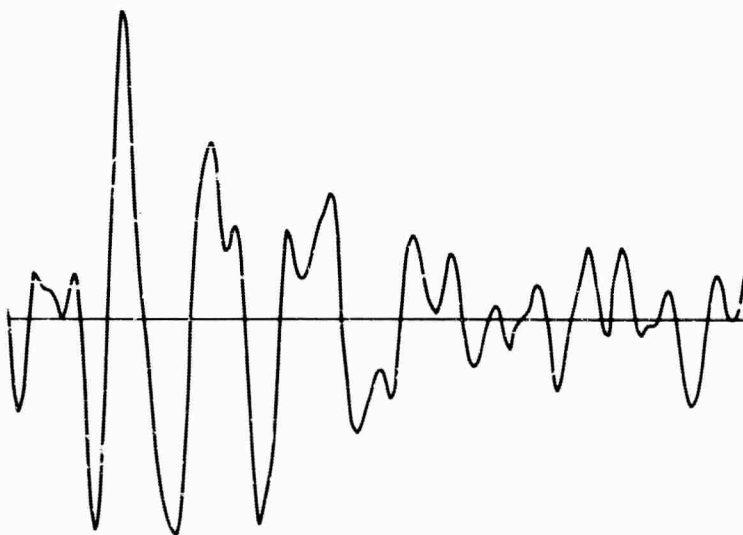
Figure 7b. Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.



18 m FILTERED



2270 m UNFILTERED



2270 m FILTERED

Figure 7c. Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.



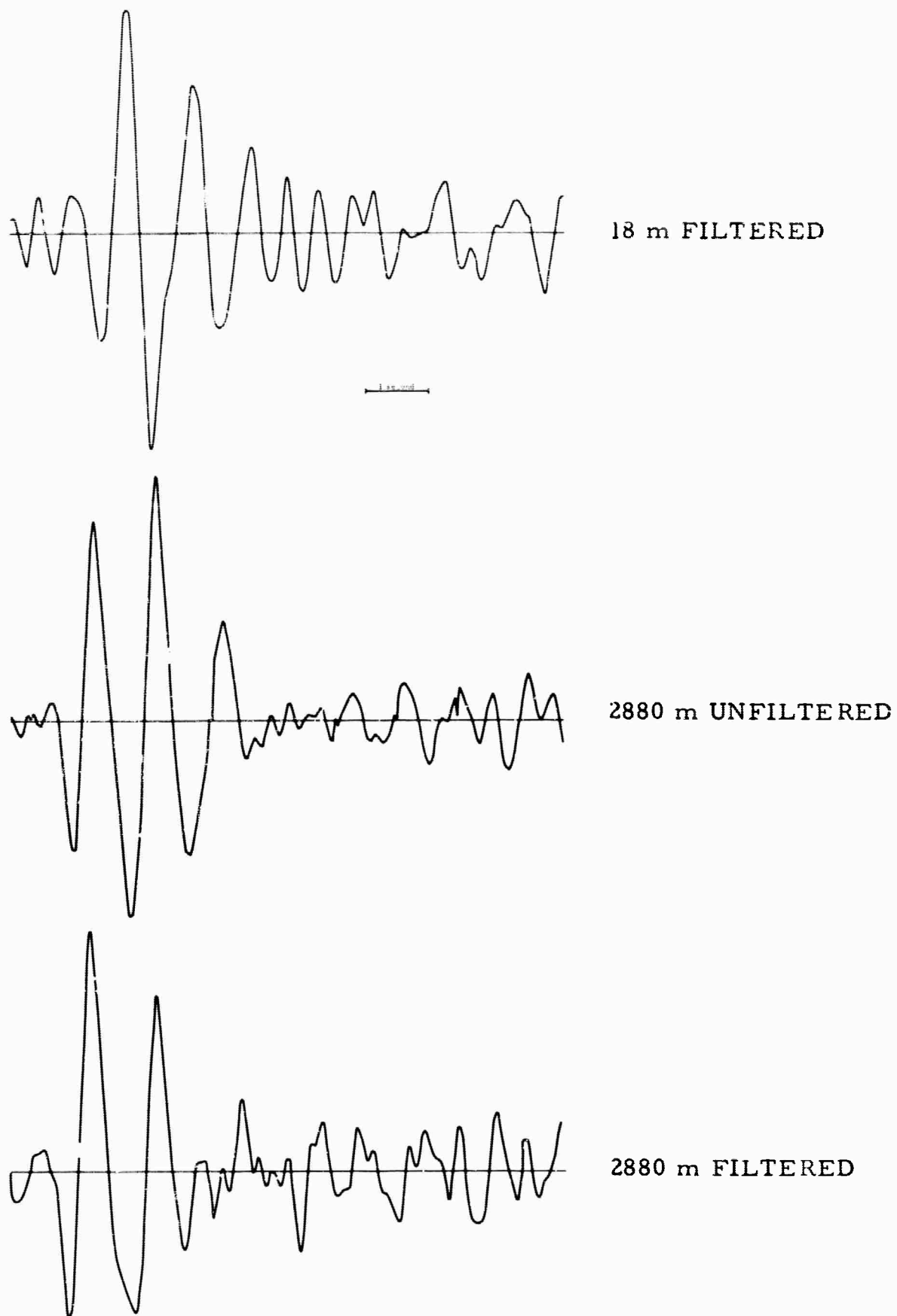


Figure 7d. Results of inverse filtering of a small teleseism at Apache, Oklahoma. Filtered and unfiltered traces are shown.

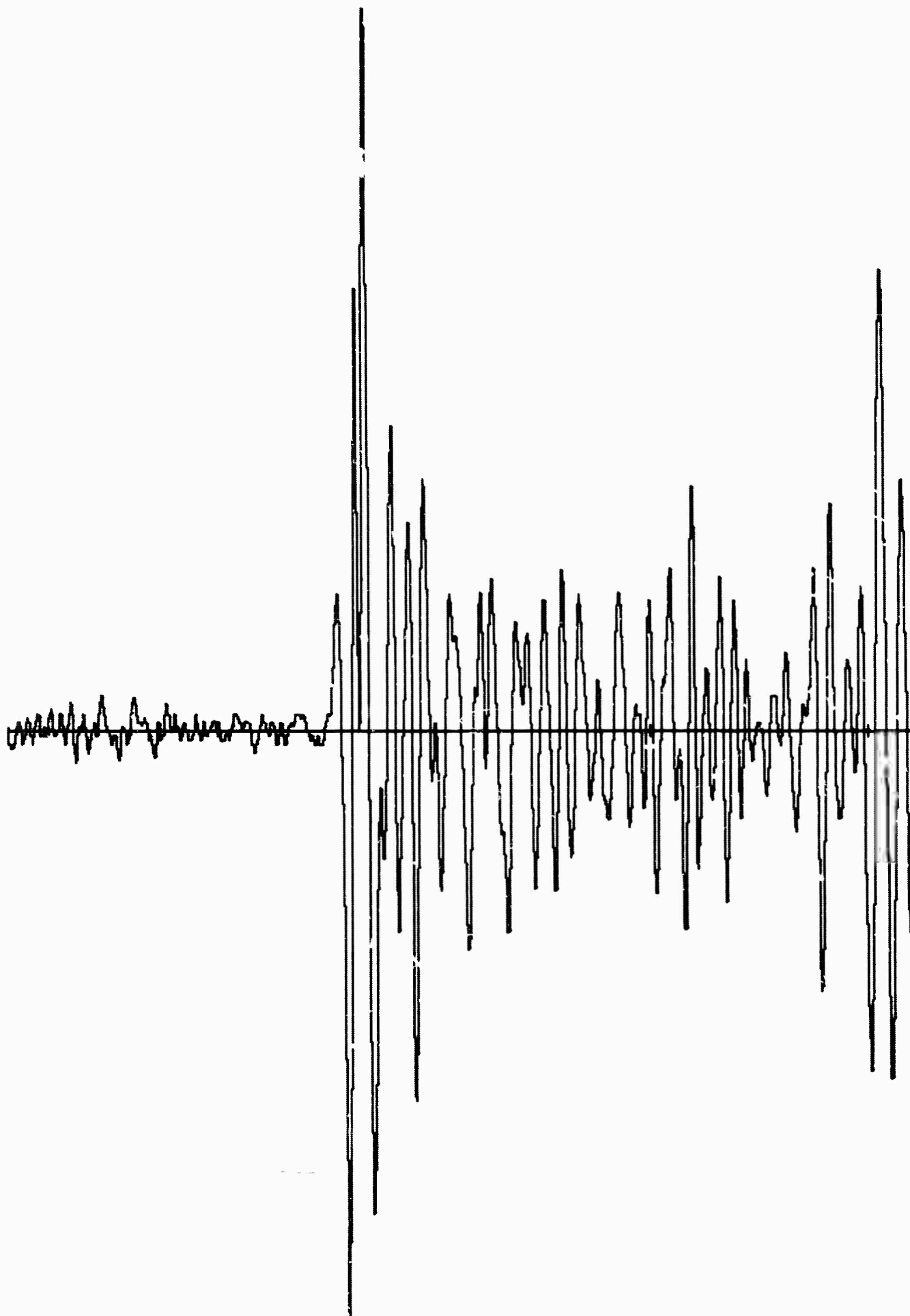


Figure 8a. Teleseism recorded at Apache, Oklahoma, by the shallow-hole (18 m) seismograph

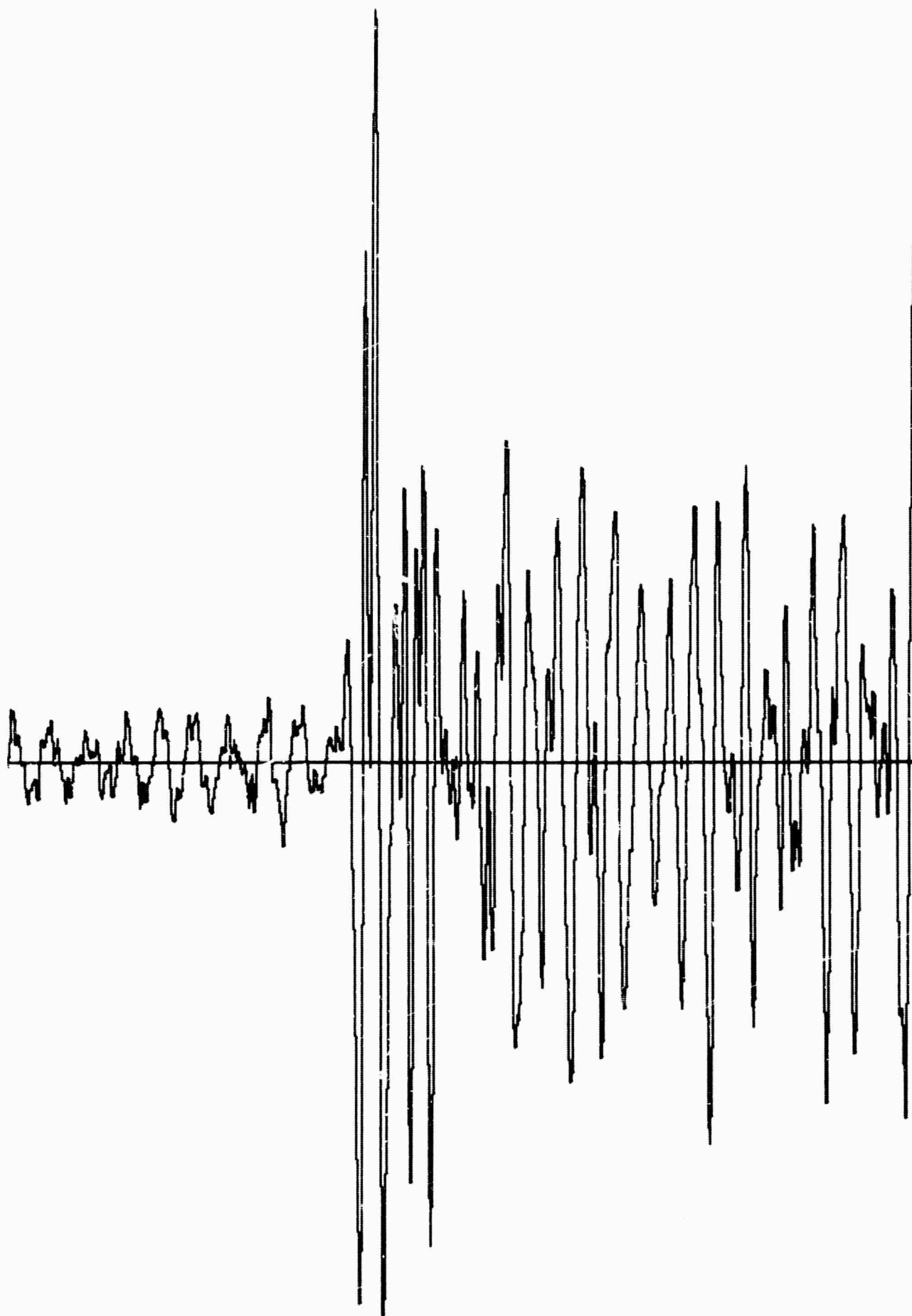


Figure 8b. Seismogram obtained at 1970 m after inverse filtering.  
Apache, Oklahoma

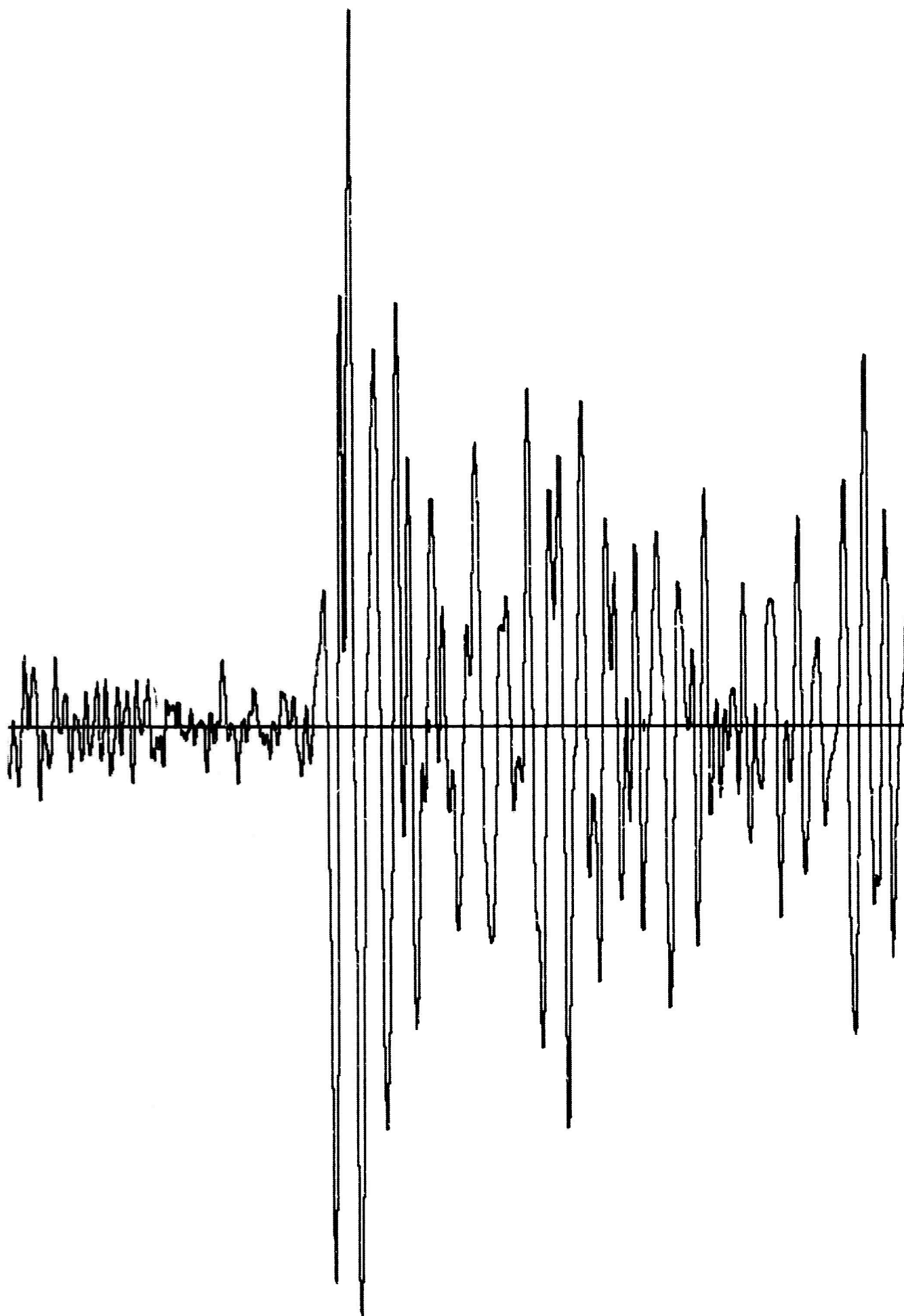


Figure 8c. Seismogram obtained at 2270 m after inverse filtering.  
Apache, Oklahoma

APPENDIX 1 TO TECHNICAL REPORT NO. 65-119

QUARTERLY REPORT NO. 1, PROJECT VT/5051  
DEEP-WELL RESEARCH

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STATEMENT OF WORK TO BE DONE  
AFTAC PROJECT AUTHORIZATION No. VELA T/5051

1. Tasks.

a. Conduct systems engineering on deep-well instrumentation to obtain a capability of operating up to 6 seismometers in a borehole simultaneously. Evaluate the applicability of multiconductor data cable with quick disconnect features between instruments in a vertical array. No major redesign of the deep-well seismometer is anticipated although mass size may be reduced to meet size and weight limitations. Following design approval by the government, assemble and conduct operational tests on the recommended deep-well seismographic system.

b. Maintain and operate the deep-well test facility near Grapevine, Texas, for the purpose of testing equipment modifications, developing new handling and emplacement techniques, and qualifying calibration and operational procedures for the deep-well seismograph. In this regard, field evaluation of new or improved deep-well devices, such as the borehole triaxial SP seismometer under Project VELA T/072, will be conducted at Grapevine prior to use in field measurements tasks.

c. Continue to measure signals and noise in deep and shallow boreholes where additional data are required. These field measurements do not anticipate any preparation of new deep-well sites but provide for occupancy of several boreholes previously conditional and available. Data should be obtained for the purpose of supporting analysis of the behavior of seismic signals and noise with depth. A limited number of shallow boreholes may be required in support of this task.

d. Provide for complete and detailed analysis of data resulting from field measurements and develop means of processing multiple signals from borehole arrays of 3 to 6 sensors. Major effort should be devoted to prediction of deep- and shallow-buried arrays under varying conditions of surface noise, environmental influences, geological structures, and geographic location. Large scale computer support of the CDC 1604 class is not authorized but will be provided by separate arrangement with the AFTAC project officer.

2. Reports.

a. A monthly letter-type management and progress report in 14 copies, summarizing work through the 25th of the month, will be dispatched to AFTAC by the end of each month. Specific topics will include technical and financial status, major accomplishments, problems encountered, future plans, and any action required by AFTAC. The financial status in each report should

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include estimated expenditures and commitments to date, estimated funds available to complete the work, and estimated excess or deficiency of funds. Illustrations and photographs should be included as applicable. In addition, the monthly report submitted for the reporting period occurring 6 months prior to the scheduled contract completion date shall contain specific statements concerning recommendations or requirements and justifications for extensions, modifications, or expiration of work and any changes in cost estimates which are anticipated by the contractor. The heading of each report should contain the following information:

AFTAC Project No. VELA T/5051  
Project Title  
ARPA Order No.  
ARPA Project Code No.  
Name of Contractor  
Date of Contract  
Amount of Contract  
Contract Number  
Contract Expiration Date  
Project Scientist's or Engineer's Name and Phone Number

b. A list of suggested milestones will be dispatched to AFTAC in 14 copies not later than 20 September 1964. Milestones are defined as accomplishments which present significant progress when completed. Each milestone should be briefly described and completion dates should be estimated. Upon arrival of milestone information, copies of SD Form 350 will be furnished for reporting progress against the milestone schedule. The SD Form 350 will be attached to the monthly report.

c. Special reports of major events will be forwarded by telephone, telegraph, or separate letter as they occur and should be included in the following monthly reports. Specific items are to include (but are not restricted to) program delays, program breakthroughs, and changes in funding requirements.

d. Special reports, as requested by the AFTAC project officer, may be required upon completion of various portions of the work.

e. An initial technical summary report in 50 copies, covering work performed through 30 January 1965, will be submitted to AFTAC within 15 days after the close of the reporting period. A semi-annual technical summary report in 50 copies, covering work performed through each 6-month period following the close of the initial reporting period, will be submitted to AFTAC within 15 days following the close of the reporting



period. These reports will present a precise and factual discussion of the technical findings and accomplishments during the reporting period. The heading of the report will contain the heading information indicated in paragraph 2a.

3. Technical Documents. The contractor will be required to furnish the following technical documents:

a. All seismograms and operating logs, to include pertinent information concerning time, date, type of instruments, magnifications, etc., as requested by the AFTAC project officer.

b. Technical manuals on the installation and operation of all technical equipment installed during the duration of the contract for this project.

c. Two sets of reproducible engineering drawings and specifications for any changes or modifications in standard operational equipment and instruments, and for any new equipment designed, together with 2 sets of prints of these same drawings.

5. Miscellaneous. DD Form 1423, Contract Data Requirement List is attached. All technical reports and documents are to be forwarded to:

Hq USAF (AFTAC/VELA Seismological  
Center/Maj Meek)  
Wash DC 20333

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AMENDED STATEMENT OF WORK TO BE DONE  
AFTAC Project Authorization No. VELA T/5051

19 May 1965

1. Tasks.

a. Under Task 1a, add: Assemble and operate 2 deep-well vertical array systems at locations designated by the AFTAC project officer. Each system will consist of up to 6 sensors suitable for borehole use and appropriate surface recording instrumentation. Ground handling equipment, derricks, rigging, and instrument winching shall be easily transportable between sites and capable of maximum flexibility in field measurements operations.

b. Under Task 1d, add: Develop, provide, and maintain an array signal processing apparatus capable of processing multiple data inputs from borehole arrays. This processing apparatus must ultimately be suitable for on-line operation and may be composed of digital as well as analog components.

2. Reports. In lieu of the report requirements in paragraphs 2a, b, c, d, and 3, provide monthly, quarterly, final, and special reports in accordance with sentence 1, paragraph 1 of Data Item S-17-12.0, AFSCM 310-1; however, if that data item conflicts with Attachment 2, Amendment 1, Project VT/5051, the latter will take precedence.

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Atch 3

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